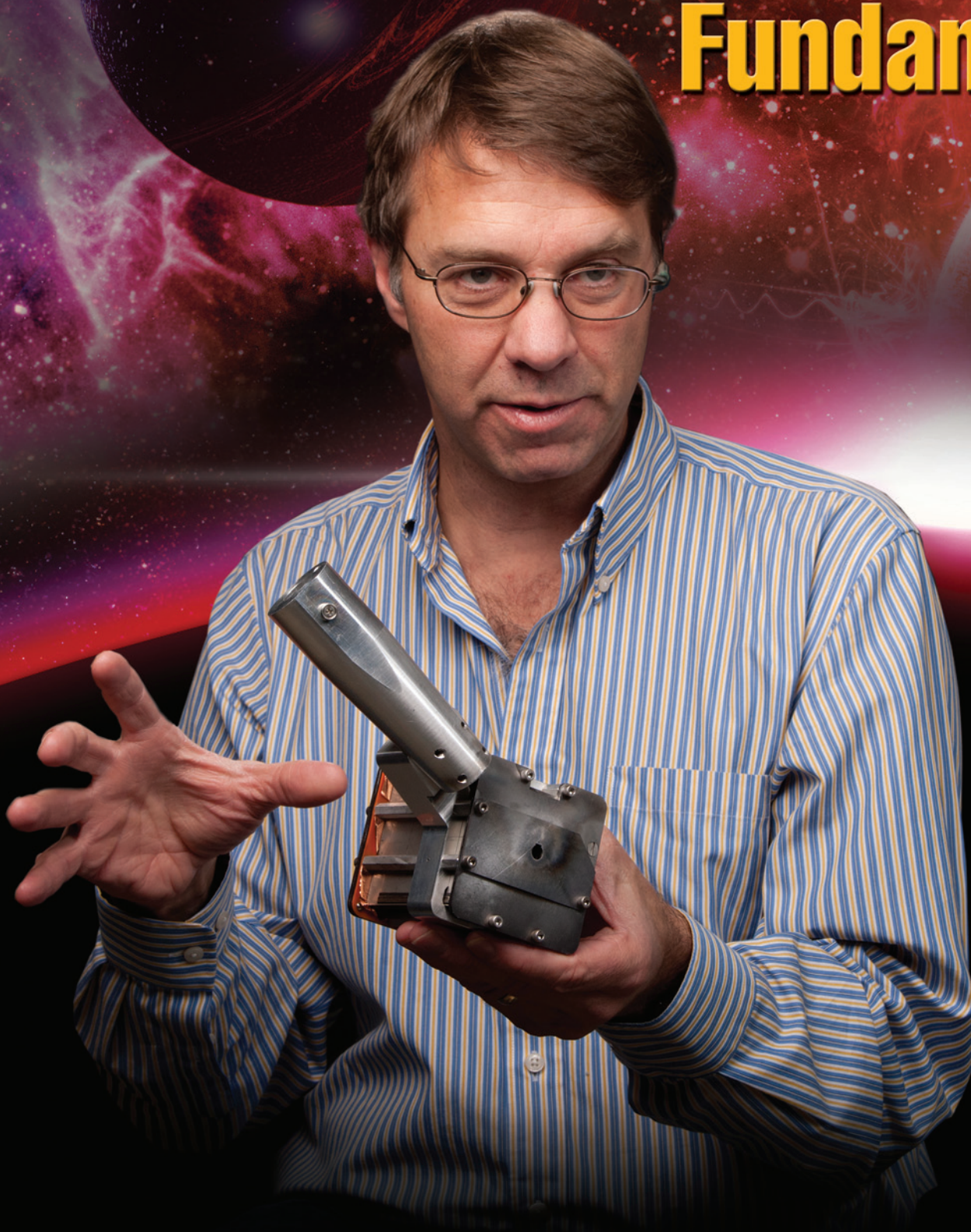


At the Fundamental



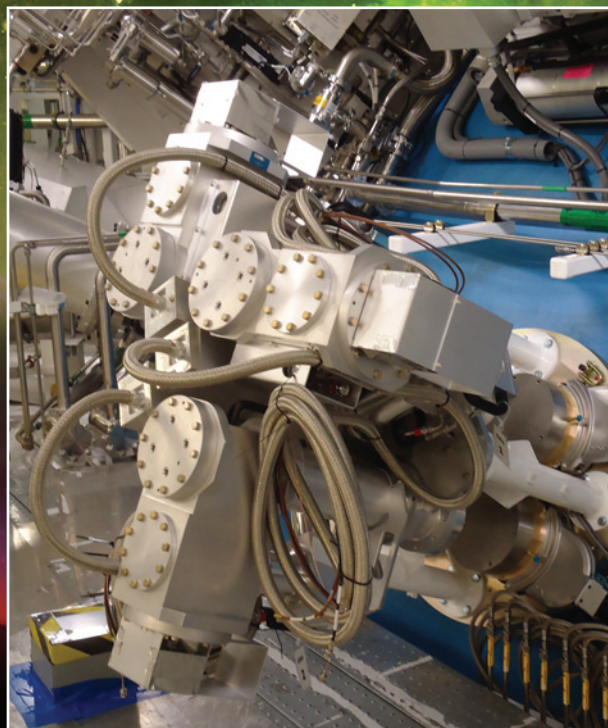
Livermore physicist Jon Eggert, shown with a powder x-ray diffraction image-plate holder, is collaborating on a fundamental science project to be conducted at the National Ignition Facility (NIF). This project is designed to study carbon under extreme pressures and thus better understand the atomic structure of diamond.

Frontiers of Science Research

The National Ignition Facility is maturing as an experimental facility and emerging as a premier resource for experiments in fundamental science.

THE National Ignition Facility (NIF), along with other new laser facilities in France, Japan, the United Kingdom, and elsewhere, is at the forefront of a significant worldwide thrust in scientific research: the study of matter under ultrahigh pressures and temperatures, conditions that have been inaccessible in laboratory experiments. Today, NIF is operating 24 hours a day. As the world's most energetic laser system, it is quickly becoming the premier facility in this exciting and rapidly evolving area of physical science. By focusing NIF's 192 laser beams onto a variety of targets, scientists for the first time can create extreme states of matter, replicating conditions that occurred during the big bang or a nuclear weapon detonation and those found at the interior of stars and planets. (See *S&TR*, June 2010, pp. 17–19; April/May 2010, pp. 4–11.)

Since NIF's completion in 2009, researchers have worked to make the giant laser's scientific promise a reality. Experiments conducted to date have achieved energies as high as 1.6 megajoules—approximately



More than 50 diagnostic systems are now online for NIF experiments. Shown here is the gamma reaction history diagnostic, which was developed for the National Ignition Campaign.

40 times greater than the level produced by other lasers—and a peak power of 420 terawatts. They have also demonstrated unprecedented shot-to-shot reproducibility as well as NIF's high-precision pulse-shaping capabilities.

The National Ignition Campaign (NIC) team and scientists working on the National Nuclear Security Administration's (NNSA's) Stockpile Stewardship Program have commissioned more than 50 optical, x-ray, gamma, neutron, and charged-particle diagnostic systems and have developed techniques to fabricate the precision targets required for all NIF experiments. (See *S&TR*, July/August 2007, pp. 12–19.) The combination of laser, target, and diagnostic capabilities available at NIF are enabling experiments in new scientific regimes. In fiscal year

2011, 286 experiments were successfully executed in a wide range of programmatic and scientific areas with diverse demands on facility time and resources.

The most visible scientific effort at NIF is the demonstration of ignition via NIC and the subsequent exploration of the physics of burning plasmas. In addition, the broader scientific community is engaged in developing NIF as a tool for fundamental science. The importance of such research has been discussed in several reports, including *Basic Research Directions for NIF User Science*, a recent workshop report published jointly by NNSA and the Department of Energy Office of Science. In addition, scientists interested in pursuing fundamental science at NIF are organizing a user group, with Justin Wark, a professor from the University of Oxford, as interim

chair. The Laboratory will host the group's first meeting February 12–15, 2012. (See the box below.)

In recognition of NIF's scientific promise and user-community interest, Livermore executed a call for proposals for fundamental science research to be conducted at the facility. This competition, held in 2009 and 2010, received a strong response, with approximately 50 percent of the proposals from U.S. academic institutions, 25 percent from laboratories or institutions outside the NNSA complex, and 25 percent from international organizations. An external committee chaired by Robert Rosner, former director of Argonne National Laboratory and now a professor at the University of Chicago, reviewed the proposals.

Ten teams, some of which were approved prior to the proposal call, are now preparing fundamental science experiments on NIF to address a range of scientific questions, from observing new states of matter to

exploring the origin of ultrahigh-energy cosmic rays. Each team is paired with a Livermore scientist, who acts as facility liaison and collaborates on experiment design and execution. To make effective use of their allotted shot time, many teams first develop their experimental laser, diagnostic, and target setups at smaller facilities, such as the OMEGA and OMEGA EP lasers at the University of Rochester's Laboratory for Laser Energetics and the Jupiter Laser Facility at Livermore. They then perform fully integrated experiments on NIF.

Material Behavior at a Planet's Core

One fundamental science project on NIF is studying how planets outside our solar system form and evolve. Over the past 16 years, nearly 700 extrasolar planets have been identified, some smaller than Earth and others a dozen times more massive than Jupiter. Observational data provides only a rough estimate of an object's size and mass, so scientists must

supplement exploration with modeling. This approach, however, has its own limitations because models are based on our own solar system, and many planetary systems do not closely resemble ours. Accessing densities and temperatures similar to those deep within planets through laboratory experiments would allow scientists to refine their calculations and models so they can better understand the structure and formation of bodies both distant and close to home.

A major factor in unraveling the interior structure of planets is accurately predicting material behavior, or determining the relevant equations of state, under extreme pressure. Equations of state are used to generate computational models that simulate material behavior, revealing for example the temperatures and pressures at which diamond melts. NIF experiments designed to replicate the conditions believed to exist in the cores of "super-Earth" extrasolar planets (those 3 to

Campus Environment Fosters an International User Community

Lawrence Livermore has made progress toward installing the infrastructure required to support the fundamental science and other NIF user communities. A campus for high-energy-density science research allows collaborators from various disciplines and different institutions to more easily work on NIF experiments. The campus also provides a venue where users from the national security, basic science, and energy communities can discuss ongoing projects and research dilemmas—interactions that facilitate a "cross-pollination" of ideas and ultimately benefit all researchers involved in NIF experiments.

The campus includes office space for visitors and a dedicated user office to facilitate work by scientists from outside the Laboratory. A visitor office provides the staffing needed to make all arrangements for short- and long-term visits by external users. The campus will also complement the resources at the Livermore Valley Open Campus. (See *S&TR*, March 2011, pp. 22–24.)

The Laboratory's vision is to operate NIF as an international user facility and to provide a research environment that allows users to obtain maximum scientific benefit from this important national resource. Chris Keane, director of the NIF User Office, says, "Our goal is for NIF to be known as a center for scientific excellence—a facility that will make significant contributions to national security, scientific discovery, and energy independence."

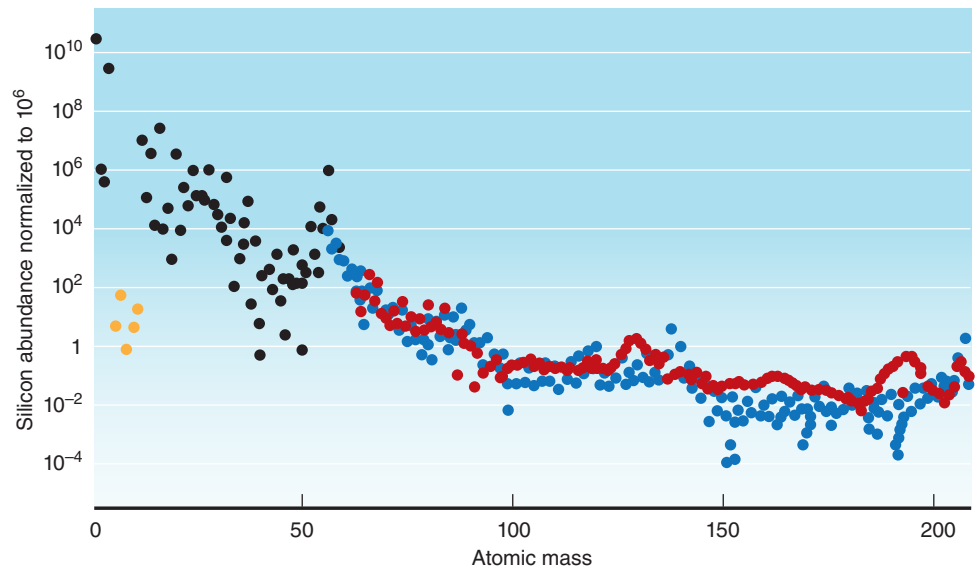


20 times more massive than Earth) will provide clues to planet formation and structure as well as to the exotic behavior of materials at high densities.

The standard technique for studying material conditions relevant to planetary interiors is through compression in a diamond anvil cell, which is limited to peak pressures near 300 gigapascals (GPa). Pressures in planetary cores, however, are higher, ranging from 350 GPa for Earth to 3,000 GPa for extrasolar planets and 7,000 GPa for Jupiter, for example. Lasers are proving to be an excellent platform for these higher pressures.

A team of scientists led by Raymond Jeanloz from the University of California at Berkeley and Tom Duffy from Princeton University has gradually compressed a diamond sample to a record pressure of 5,000 GPa (50 million times Earth's atmospheric pressure). This experiment at NIF reached more than six times the previous highest measurement, a record set by the same team using the OMEGA laser.

The researchers have also developed a time-dependent, ramp-wave compression



This plot shows abundance of elements formed during the big bang and carbon–nitrogen–oxygen burning in stars (black dots), by cosmic rays (gold dots), and by complex processes in stars that result in elements heavier than iron and nickel. NIF can be used to study the slow (s) process (blue dots), which burns the helium shell to form asymptotic giant-branch stars, and the rapid (r) process (red dots), which creates Type II supernovae and merging neutron stars. (Data adapted from E. Anders and N. Grevesse and from F. Kappeler, H. Beer, and K. Wisshak.)

technique to keep the compressed material relatively cool—less than 10,000 kelvins compared with 30 million kelvins in NIC ignition targets. With ramp compression, materials also remain in solid form at higher pressures than they would in standard, nearly instantaneous shock physics experiments. (See *S&TR*, June 2009, pp. 22–23; July/August 2007, pp. 20–21.) “The reduced level of heating offered by ramp-wave compression makes these experiments relevant to the study of planetary interiors,” says Livermore physicist Ray Smith, the project liaison.

Data are gathered with the Velocity Interferometer System for Any Reflector (VISAR), which is also used extensively in NIC experiments. VISAR records velocity versus time at various points in the target during the ramp compression. Measuring how a material such as carbon responds to stress compression will help researchers determine its equations of state and the different structures it may take as it evolves under extreme pressure.

Carbon in its many forms, including diamond, is of great interest to planetary researchers. Icy, giant planets such as Uranus and Neptune contain large quantities of methane, which decomposes at high pressures and temperatures and thus may form interior diamond-rich layers. Previous shock experiments and an earlier series of ramp compression experiments on OMEGA have furthered the understanding of diamond phases and material strength. Before the NIF experiments, however, researchers had not explored the behavior of diamond in solid state from 1,000 to 10,000 GPa.

Smith notes that NIF's laser pulse-shaping capability was also critical to the team's success. Researchers had to customize the pulse shape precisely to match the material being compressed. Otherwise, the laser pulse might have generated a shock and melted the sample. These NIF experiments are the first to demonstrate that scientists can access the relevant pressure regime for extrasolar planet interiors.



In upcoming experiments, Smith's team hopes to push even further into the high-pressure regime with diamond—up to 10,000 GPa. The researchers will then apply ramp compression to examine other materials relevant to planetary interiors, such as iron. They are eager to study iron's compressibility and crystal structure because supermassive planets are expected to have an iron core. The ramp compression techniques are also being used in NIF stockpile stewardship experiments on tantalum, which are already producing initial evidence of a new high-pressure phase.

A related fundamental science experiment will explore carbon using ramp compression and an x-ray diffraction diagnostic that is under development. The goal of this effort is to observe the atomic structure of diamond (and later, other materials) as it is compressed. The traditional view among physicists has been that materials have a simple structure at high pressure. New observations, however, indicate increased structural and behavioral complexity for many materials.

Theoretical calculations predict that at ultrahigh pressure, carbon will undergo several phase transitions. One of these phases, BC8, is thought to have similar

atom bonding as that found in diamond. The university team, led by Wark and Jon Eggert at Livermore, plans to look for evidence of a phase transition to BC8.

Accelerating Element Formation

Nucleosynthesis, or element formation, occurs at extreme stellar temperatures and pressures, making it difficult to simulate in the laboratory. (See *S&TR*, July/August 2007, pp. 22–23.) Elements heavier than iron are formed either slowly, during the life of a star, or rapidly, during a star's last few seconds. NIF can more realistically replicate the hot, dense stellar plasma where both processes occur in nature than is possible in other laboratory experiments. Livermore physicist Lee Bernstein leads a project to study the slow nucleosynthesis process, or s-process, deep within asymptotic giant branch stars.

Two important reactions occur during the s-process. In neutron capture, the mass of the nucleus increases by one unit, while the charge stays constant. In beta decay, the charge of the nucleus increases or decreases, and the mass remains unchanged. For neutron capture to occur, free neutrons must be available, but an unstable nucleus undergoes beta decay automatically and then waits for the next neutron capture.

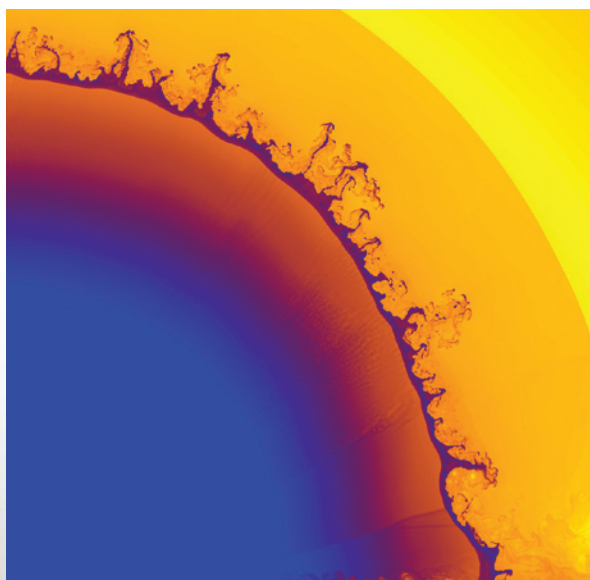
Sometimes, capture rates are comparable to the rate of beta decay by a particular isotope, forming a “branch point” in the s-process. A portion of that isotope will undergo neutron capture, while another portion transforms through beta decay. The likelihood for a particular isotope to take a given path depends on how easily a neutron can hit the nucleus, which in turn depends on physical conditions such as temperature and neutron density inside the star.

Accelerator experiments have measured the rates for neutron capture and beta decay, called cross sections, for most stable nuclei. However, measuring cross sections of unstable, short-lived nuclei has been impossible, in part because such studies would require unsafe quantities of radioactive materials. Models that extrapolate cross sections from stable nuclei and apply them to unstable nuclei are limited in accuracy. Another complication is that nuclei in a stellar plasma often exist in excited states that modify capture probability.

“If we could determine these capture probabilities, then the s-process could tell us amazing things,” says Bernstein. “We could use the information to help determine the heat, compression, and density of star interiors.” Knowing the neutron capture processes and probabilities would also improve star and planetary formation models and could explain big bang nucleosynthesis puzzles, such as the unexpected abundance of certain isotopes in the universe. Accessing the hot, dense stellar environment is important for stockpile stewardship as well.

NIF holds some advantages over accelerators—and nature. Laser experiments require a much smaller quantity of radioactive material than accelerators would, allowing the experiments to be safely performed. Radioactive (or short-lived) elements can also be directly created at NIF, but not in accelerators. When bombarding a tiny fuel pellet with laser energy, scientists can produce stellar conditions with much higher neutron quantities. In

One series of NIF experiments is studying hydrodynamic instabilities in supernovae. This simulation, created by team member Tomasz Plewa from Florida State University, shows Rayleigh–Taylor instability growth during a supernova in a red supergiant star.



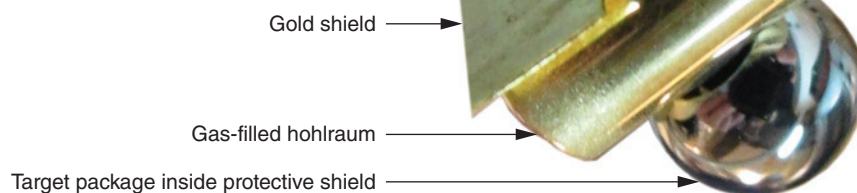
addition, the laser energy compresses the target, reducing its area by a factor of 1,000, boosting the density of nuclei, and increasing the probability of a neutron hitting a nucleus. Because of the additional neutrons and the extremely dense target material, an astonishing 2,800 years of stellar neutron capture occurs in every NIF shot. Even for short-lived nuclei, multiple reactions are possible in a single shot, potentially advancing scientific understanding of nucleosynthesis far more rapidly than accelerator-based experiments.

Livermore physicist Dick Fortner, who works on the nucleosynthesis project, says, “The first key physics question is can we generate and measure low-energy neutrons to simulate the conditions the astrophysics community is interested in?” Fast-moving, high-energy neutrons generated by a typical NIC experiment hit the wall of the target chamber, lose energy, and generate a background signal that interferes with astrophysically relevant, low-energy neutron measurements. In fact, most neutrons hit the wall a fraction of a second after the experiment. The team needed a device that could rapidly detect and measure low-energy neutrons before the more energetic neutrons have a chance to muddy the signal.

The gamma reaction history (GRH) diagnostic proved to be ideal for this purpose. This tool was developed for NIC experiments by a team led by Wolfgang Stoeffl at Livermore and Hans Herrmann at Los Alamos. When the relevant low-energy neutrons exit the gold target enclosure (or hohlraum), neutrons are captured on the gold, just as they would be in a star. This process generates a surge of gamma rays detectable by the GRH diagnostic, which consists of four detectors operating at independently tuned energy thresholds.

Analysis of GRH data from a 2011 shot provided the first evidence of a low-energy neutron signal in the laboratory. More low-energy neutrons were produced than predicted, by a factor of two or three. To date, says Bernstein, the team has used NIC shots for detection, calibration,

In supernova experiments on NIF, a target package is attached to the side of the hohlraum inside a thin, aluminum-coated plastic shell. The shell protects the package from the unconverted light in the target chamber.



and preliminary data gathering. Future experiments to be fielded on NIF will focus exclusively on nuclear physics research, using target fuels that maximize low-energy neutron production.

The team eventually aims to measure branch-point cross sections for nuclei in both ground and excited states and study nuclear processes within a plasma on NIF. Although the work is still in the early stages, the neutron-generation results suggest that NIF will be a powerful tool for exploring nuclear physics. Meanwhile, the analysis of GRH low-energy neutron data is helping NIC scientists better understand and interpret the ignition-relevant data the diagnostic produces.

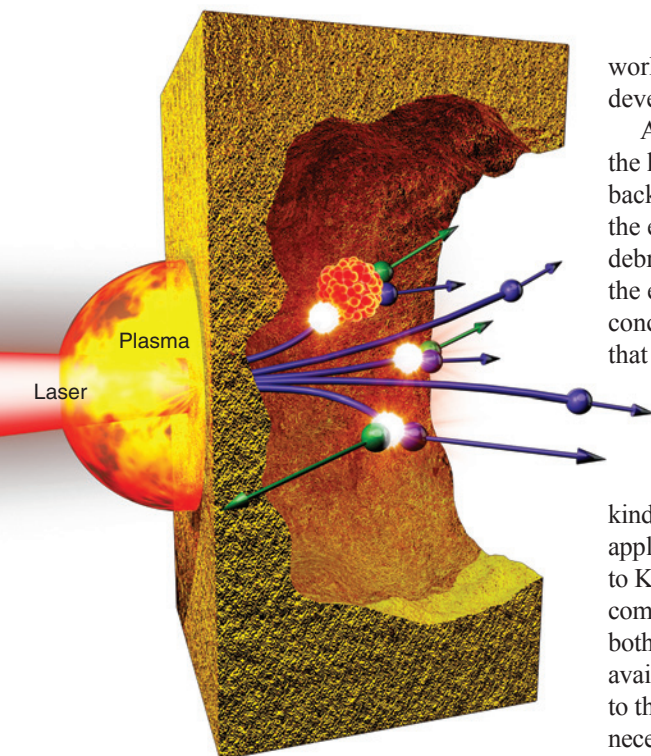
Simulating Supernovae

Another fundamental science project at NIF is investigating the evolution of turbulence in supernova explosions. In a core-collapse supernova, a star with 10 times or more mass than our Sun uses up the nuclear fuel at its core element by element, starting with hydrogen and working up the periodic table. As each fuel is consumed, the star develops an onionlike structure, with layers differing in density and material.

Once the fusion process can no longer compete with the pull of gravity, the star's core collapses in a few seconds, triggering a powerful explosion that sends a shock wave back through the star. Propelled by the shock wave, fingers of matter from heavier layers penetrate the overlying lighter shells, resulting in Rayleigh–Taylor hydrodynamic instabilities.

A research team led by Carolyn Kuranz from the University of Michigan has begun a series of NIF experiments to understand how an unstable interface is affected when heated by a shock in a supernova explosion.

To simulate this process in scaled experiments, the researchers will use the laser beams to create the extreme radiation, temperature, and pressure conditions of a supernova-type environment. They will then observe the changes in a rippled target package via x-ray radiography. The targets are designed to enhance the radiographic contrast between the rippled iodine-doped polystyrene component, which mimics the dense supernova core, and the foam component, which mimics the interstellar medium. Measuring the ripple growth will provide information on supernova evolution, in particular, how it is affected by the extremely radiative conditions.



In positron generation experiments, the short-pulse Titan laser fires a tightly focused “photon bullet” at a tiny gold disk. The laser tears electrons from their atoms and accelerates them through the gold target. As high-energy electrons interact with the gold nuclei, they are transformed into a lower energy electron (green) and its mirror, a positron (purple). (Rendering by Kwei-Yu Chu.)

Preliminary investigations to validate the experimental design are already yielding important results. A by-product of this work was a high-energy hohlraum imager that is now used for most NIF experiments.

Measurements taken with DANTE and other diagnostics have demonstrated a radiation temperature on NIF equivalent to 330 electronvolts (roughly 3.8 million kelvins), one of the highest ever recorded in a gas-filled hohlraum. This temperature surpasses the 300 electronvolts required to replicate supernova conditions. The team was surprised to find that the shot produced much higher levels of x-ray background than expected. Hye-Sook Park, a veteran NIF experimentalist and the liaison scientist for the supernova

work, notes, “We always have surprises in developing NIF-class experiments.”

Adding thicker gold shielding to the hohlraum would ensure that the background signal did not overwhelm the emissions being studied. However, debris ejected from the shield during the experiment could skew results. This concern prompted the team to request that simulations be performed to predict debris behavior.

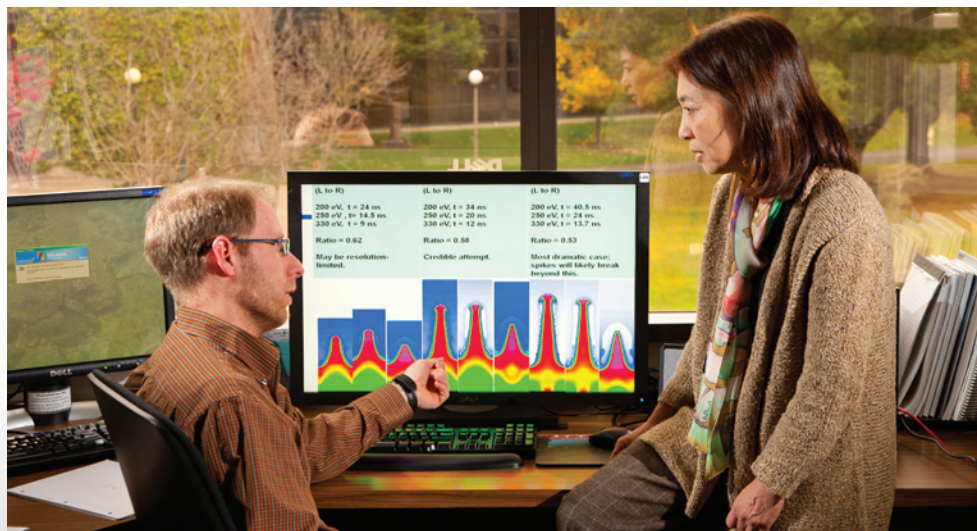
The three-dimensional calculations run on Laboratory supercomputers were perhaps the most complex of their kind performed to date and are now being applied to other experiments. According to Kuranz, access to the Laboratory’s computing capabilities—which include both codes and computing power not available at universities—has been essential to this project, whether calculating the necessary hohlraum temperature for the experiments or determining the behavior of experimental debris.

The next step for the team will be to perform integrated experiments to record instability growth in the rippled NIF targets at several radiation temperatures. Simulations indicate that x-ray radiation may stabilize the instabilities. If results

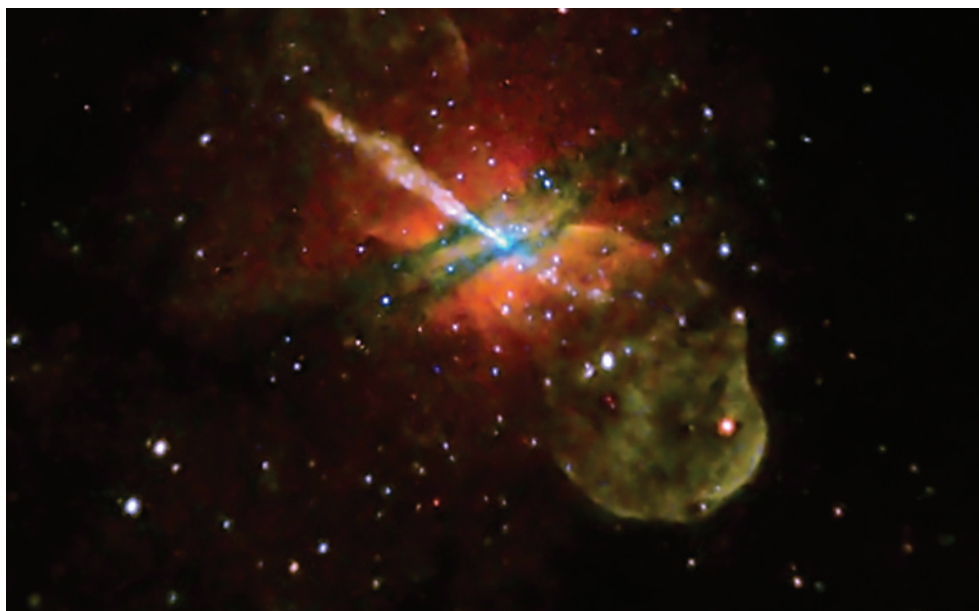
from NIF experiments verify this effect, they will offer important insight into supernova hydrodynamics. Supernovae occur only once every few hundred years in our galaxy. Supplementing astronomical observation with scaled laboratory experiments provides the best opportunity of understanding these brief and violent events, elements of which also shed light on ignition experiments and nuclear weapon detonations.

Another NIF astrophysics project aims to produce the first relativistic electron–positron pair plasmas in a laboratory, enabling experiments on a state of matter found only in gamma-ray bursts, black holes, active galaxies, and the universe shortly after the big bang. Scientists first theorized nearly 40 years ago that ultraintense lasers could generate antimatter. In the 1990s, small numbers of positrons were produced using the Laboratory’s Nova petawatt laser. Experiments in 2008 on the short-pulse Titan laser at the Jupiter Laser Facility were the first to generate a substantial source of antimatter, or positrons, using a laser.

Within tens of picoseconds, each shot on Titan creates about 10 billion positrons. This rate is several orders of magnitude greater



Aaron Miles (left) and Hye-Sook Park discuss the simulation results of diagnostic predictions for NIF experiments designed to replicate the conditions of a supernova.



Future NIF experiments are being designed to produce electron–positron jets to study what may lie at the heart of the universe's brightest objects: split-second gamma-ray bursts generated by black holes. In this image of Centaurus A taken by the Chandra X-Ray Observatory, opposing jets of high-energy particles extend from a supermassive black hole. (Courtesy of National Aeronautics and Space Administration, Chandra X-Ray Observatory, Harvard-Smithsonian Center for Astrophysics, and R. Kraft et al.)

than positron production from radioactive decay processes and is comparable to that in large-scale linear accelerators, the only other positron sources available to scientists. Physicist Hui Chen leads the team of researchers who performed the groundbreaking Titan experiments and will soon be bringing this research to NIF.

The team's experiments are producing jets with several times more electrons than positrons. To better imitate nature, the researchers are working to produce a higher density, charge-neutral jet with equal numbers of electrons and positrons. This charge-neutral jet is expected to be produced in NIF experiments using the Advanced Radiographic Capability. (See *S&TR*, December 2011, pp. 12–15.)

"If we can produce an antimatter plasma at a relativistic regime, it will help us understand many fundamental plasma physics processes," says Chen. Though the experiments are in the early stages, powerful lasers are proving to be the first available tools to access the antimatter plasma phenomena observed in nature. Ultimately, colliding two such charge-neutral jets may provide a tool to simulate gamma-ray bursts and other exotic astrophysical phenomena.

Research to Capture the Imagination

NIF's array of experimental capabilities is revealing the laser's potential as a frontier science platform. "Experience shows that open user facilities—operating as they do with a healthy mix of collaboration and competition—lead to the best ideas and high-quality science," says Wark. The promise of an open user facility with extraordinary capabilities has drawn strong interest from the international scientific community. As more results are published in papers and presented in conferences, demand is only expected to grow.

Fundamental science research offers many practical benefits for the Laboratory. Bill Goldstein, associate director for Physical and Life Sciences, is a strong supporter of this type of research. "Advancing fundamental scientific understanding is critical to the Lab's national security mission," he says. "Such work frequently leads to solutions for the hardest applied problems the Lab faces." Much of the fundamental science research will benefit NIF and other Livermore mission areas.

In addition, these experiments will help the Laboratory attract and retain top scientists because the nature of such

work captures the imagination. Says Wark, "The most exciting aspect of fundamental science experiments on NIF is that they will allow scientists to 'visit' parts of the universe we have never before been able to access." Planetary scientists and astronomers have had to collect light and particles to study distant objects. But now, for a brief moment in time, they can create a tiny sun, or the center of a giant planet, in the laboratory. Those few billionths of a second are long enough to gather detailed information about an object's properties and start unraveling the mysteries about the birth, life, and death of stars and planets.

—Rose Hansen

Key Words: antimatter, beta decay, high energy density, hohlraum, hydrodynamic instability, materials science, National Ignition Campaign (NIC), National Ignition Facility (NIF), neutron capture, nucleosynthesis, phase transition, positron, ramp-wave compression, Rayleigh–Taylor effect, s-process, stellar plasma, stockpile stewardship, supernova, x-ray diffraction.

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